SSim: NASA Mars Rover Robotics Flight Software Simulation

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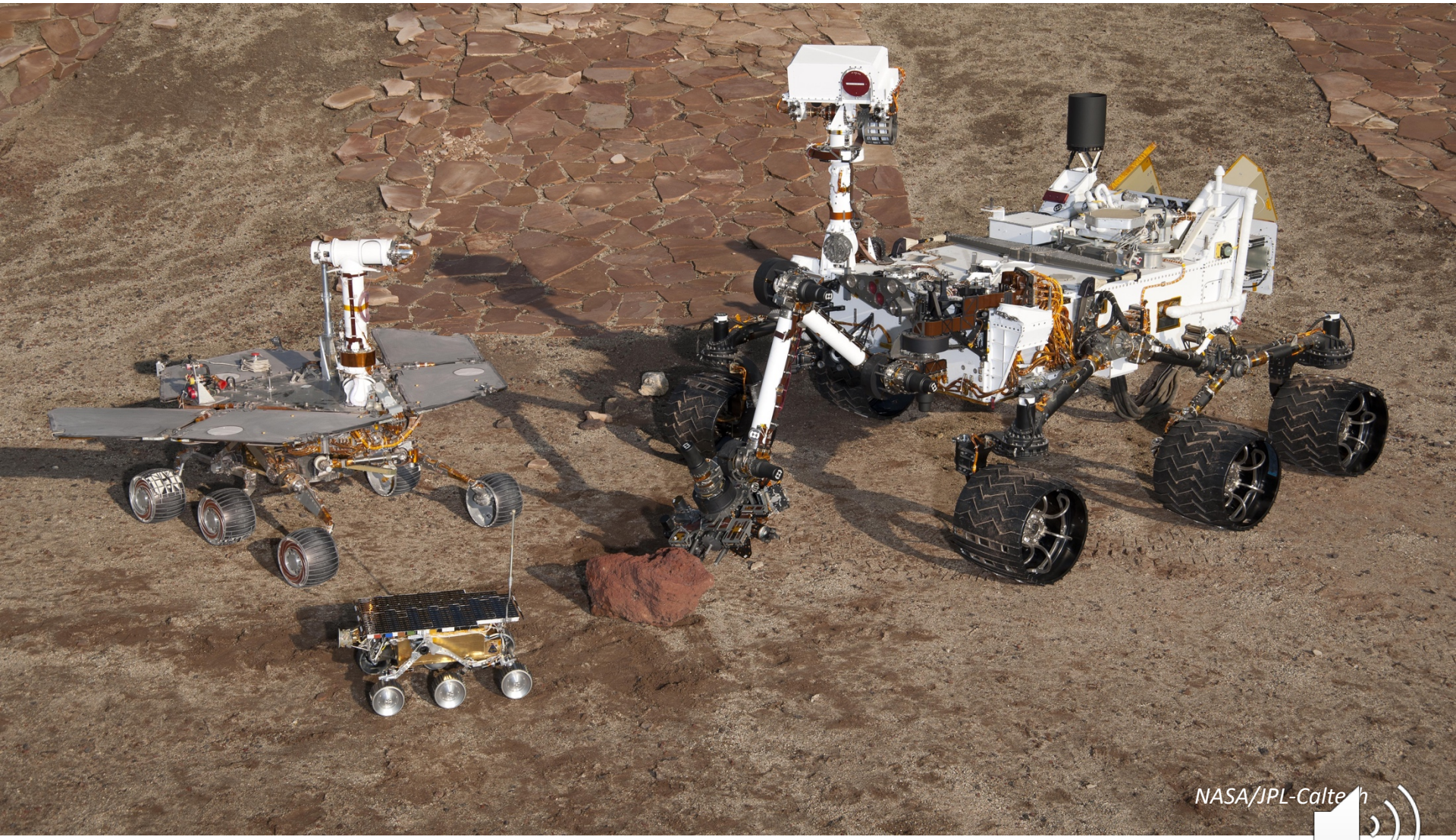
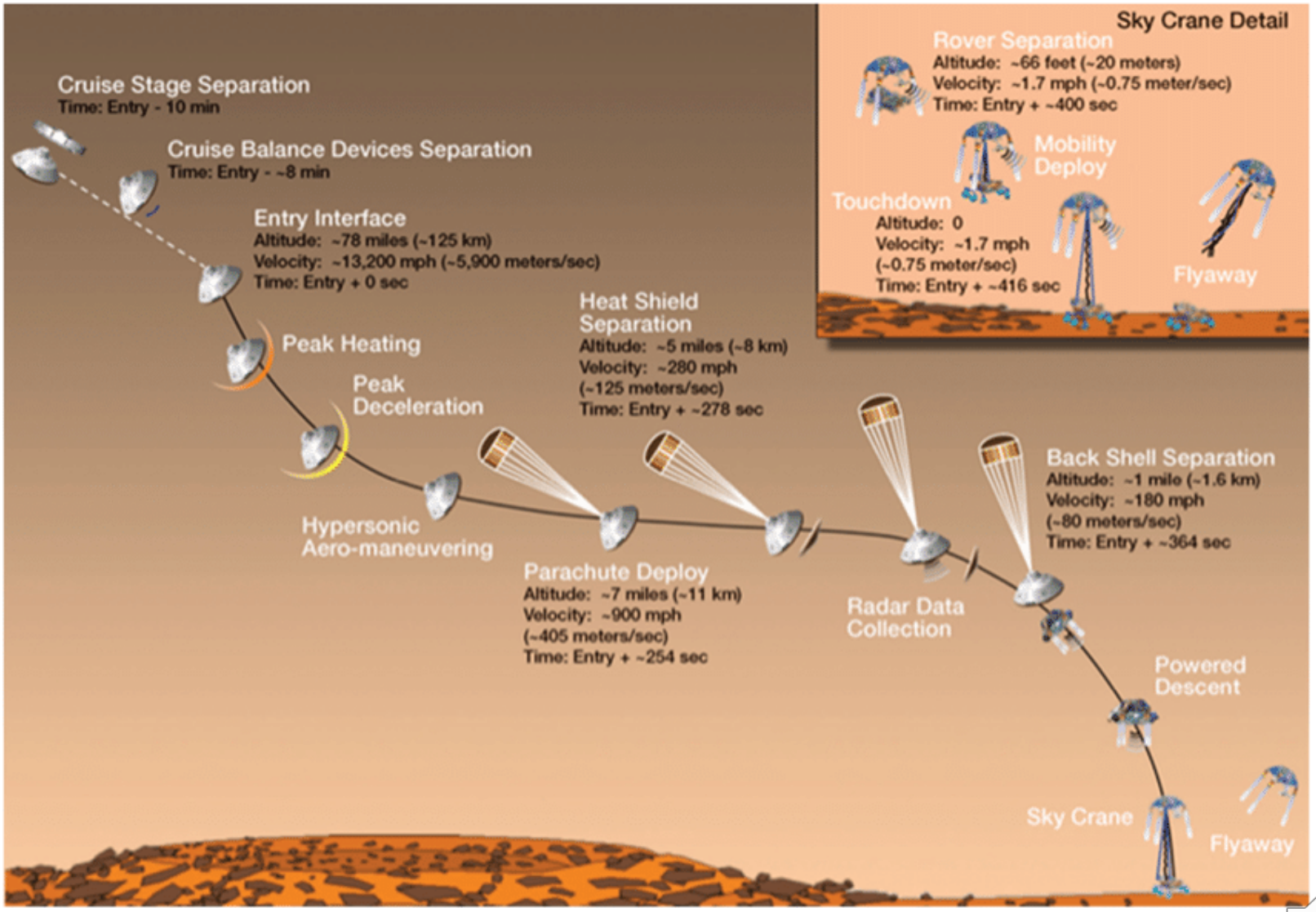
IEEE Aerospace Conference

PAST AND CURRENT



ENTRY DESCENT AND LANDING

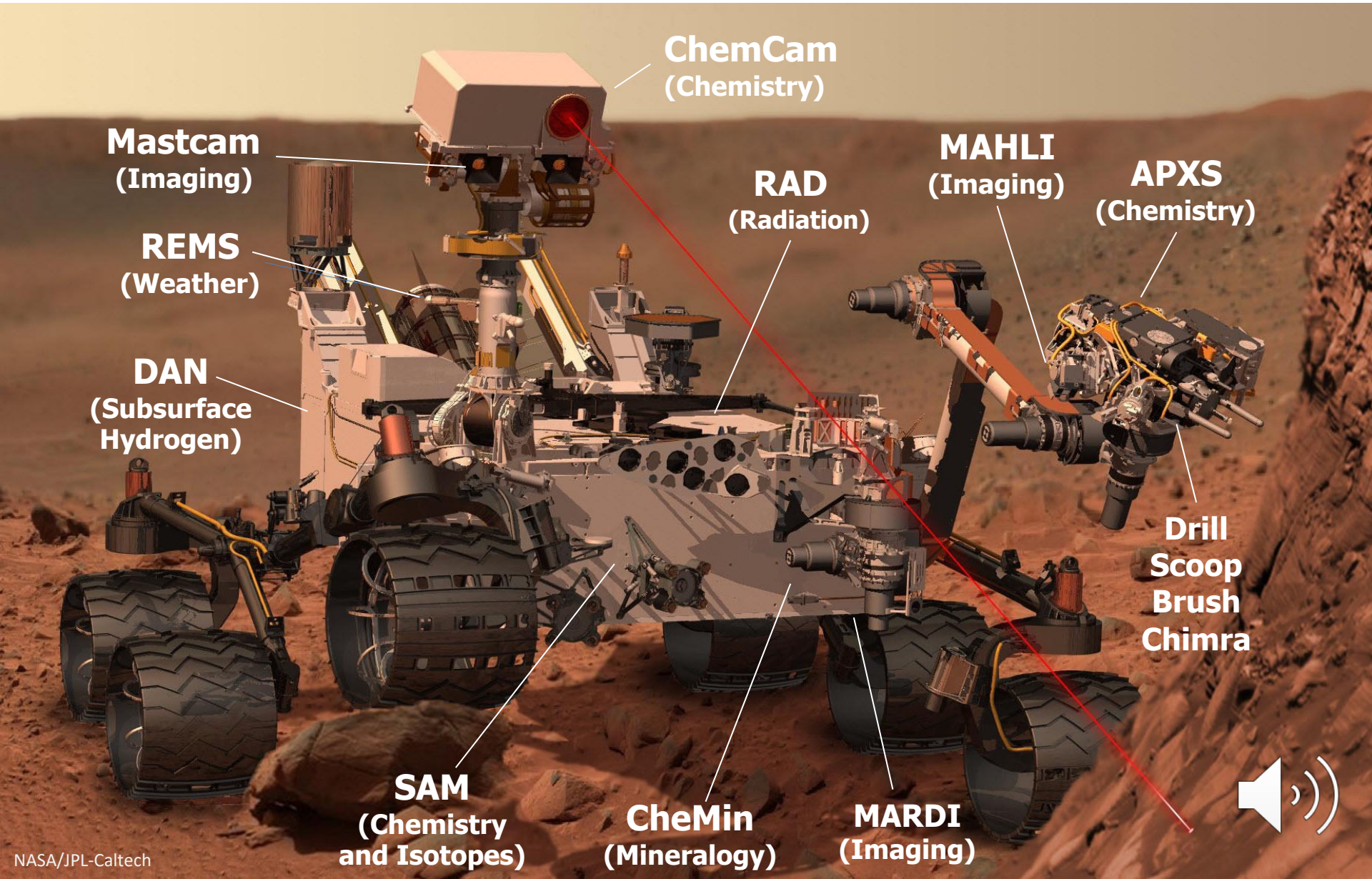


FLIGHT SOFTWARE

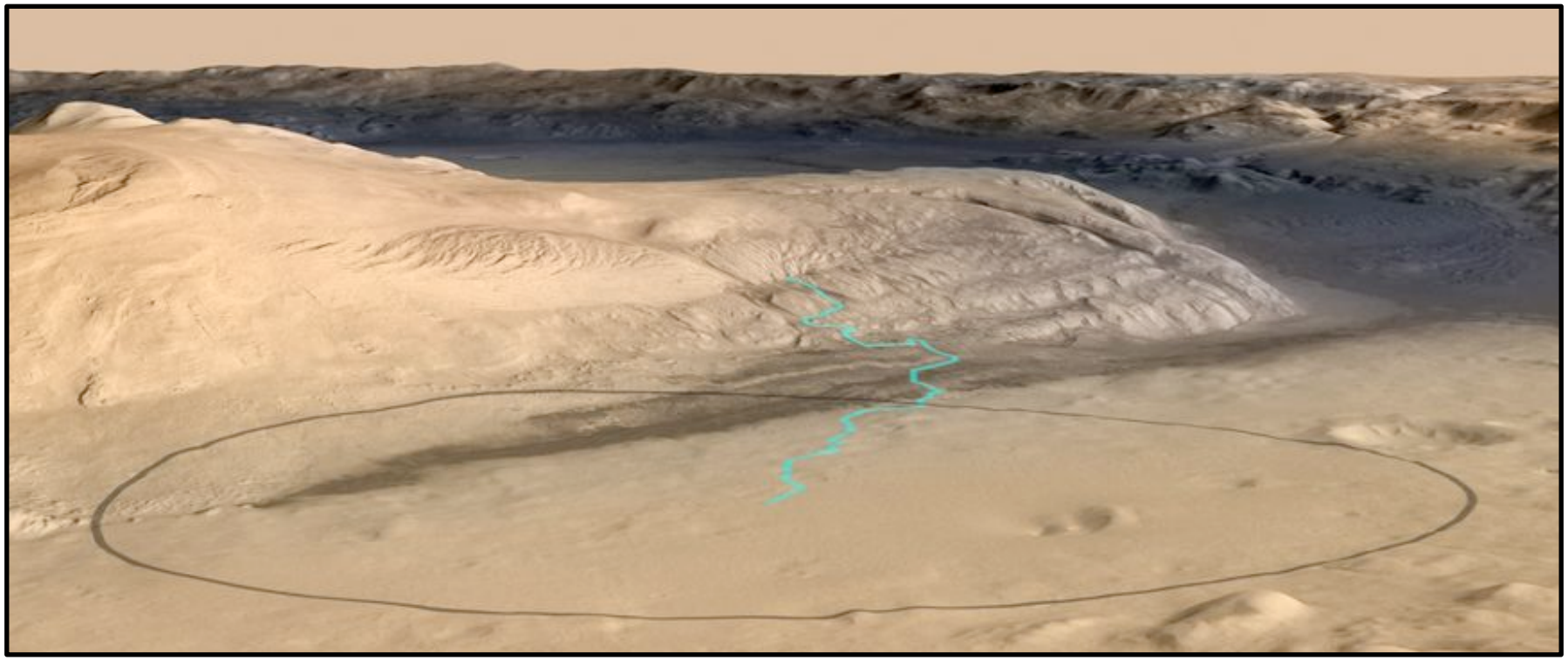
"I'm not worried that the radar will not perform. We've tested the hell out of that, and we got good performance off the radar. I'm not worried that the engines are not going to fire. I'm not worried that the parachute's not going to inflate, but I am worried that there's a bug in the software that we haven't caught yet, and that we don't know about, and it will come and bite us on a bad day."

— MSL Project Manager, Pete Theisinger, from the August 1, 2011 issue of Aviation Week

SCIENCE PAYLOAD

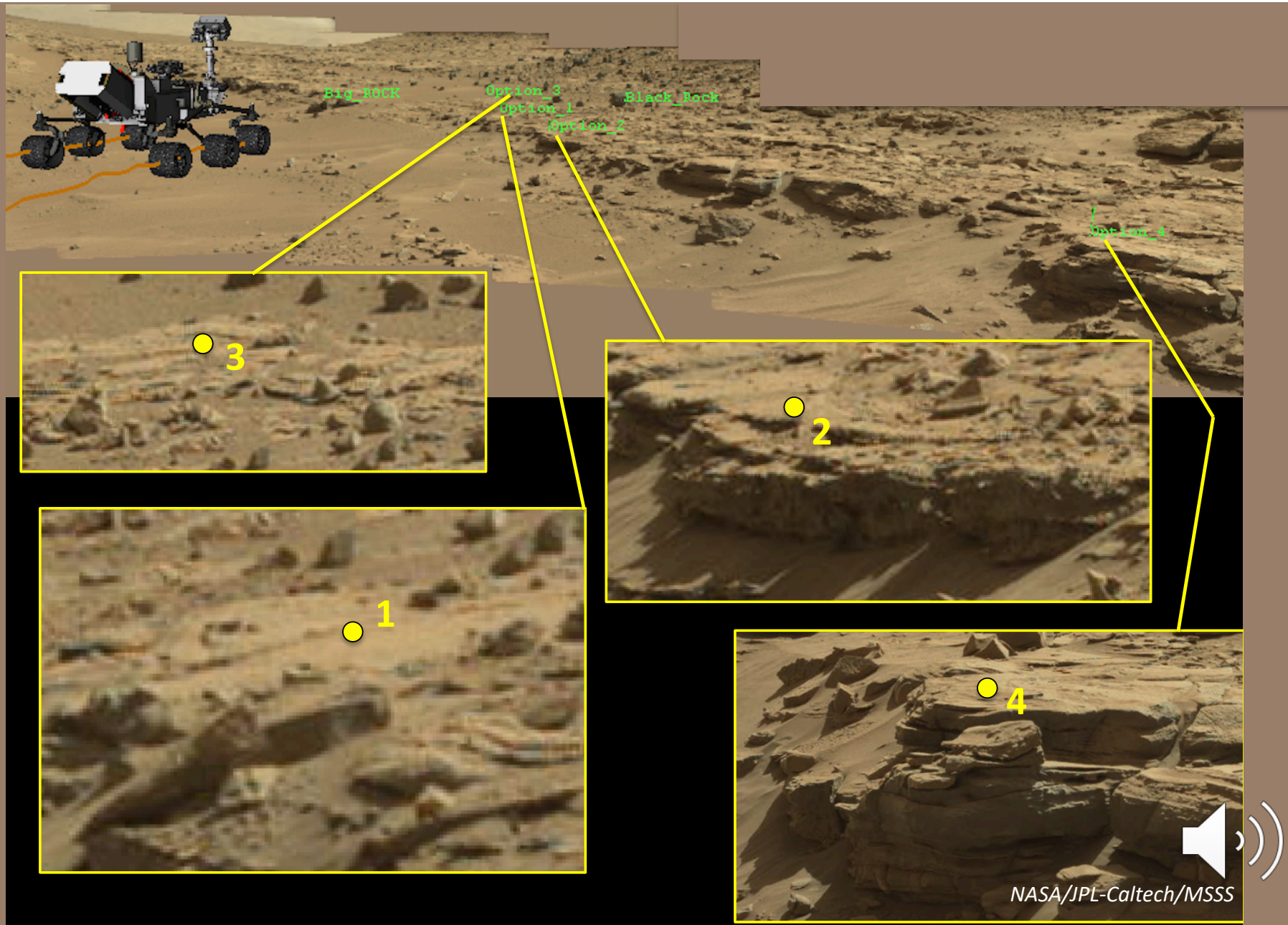


MOUNT SHARP



NASA/JPL-Caltech/Goddard

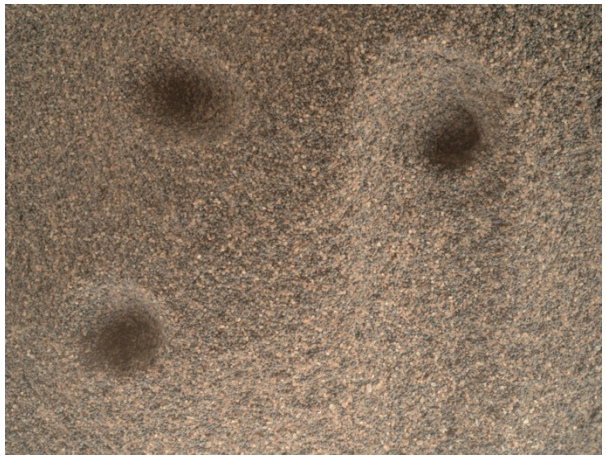
EVALUATING POSSIBLE DRILL TARGETS



NASA/JPL-Caltech/MSSS

CONTACT SCIENCE

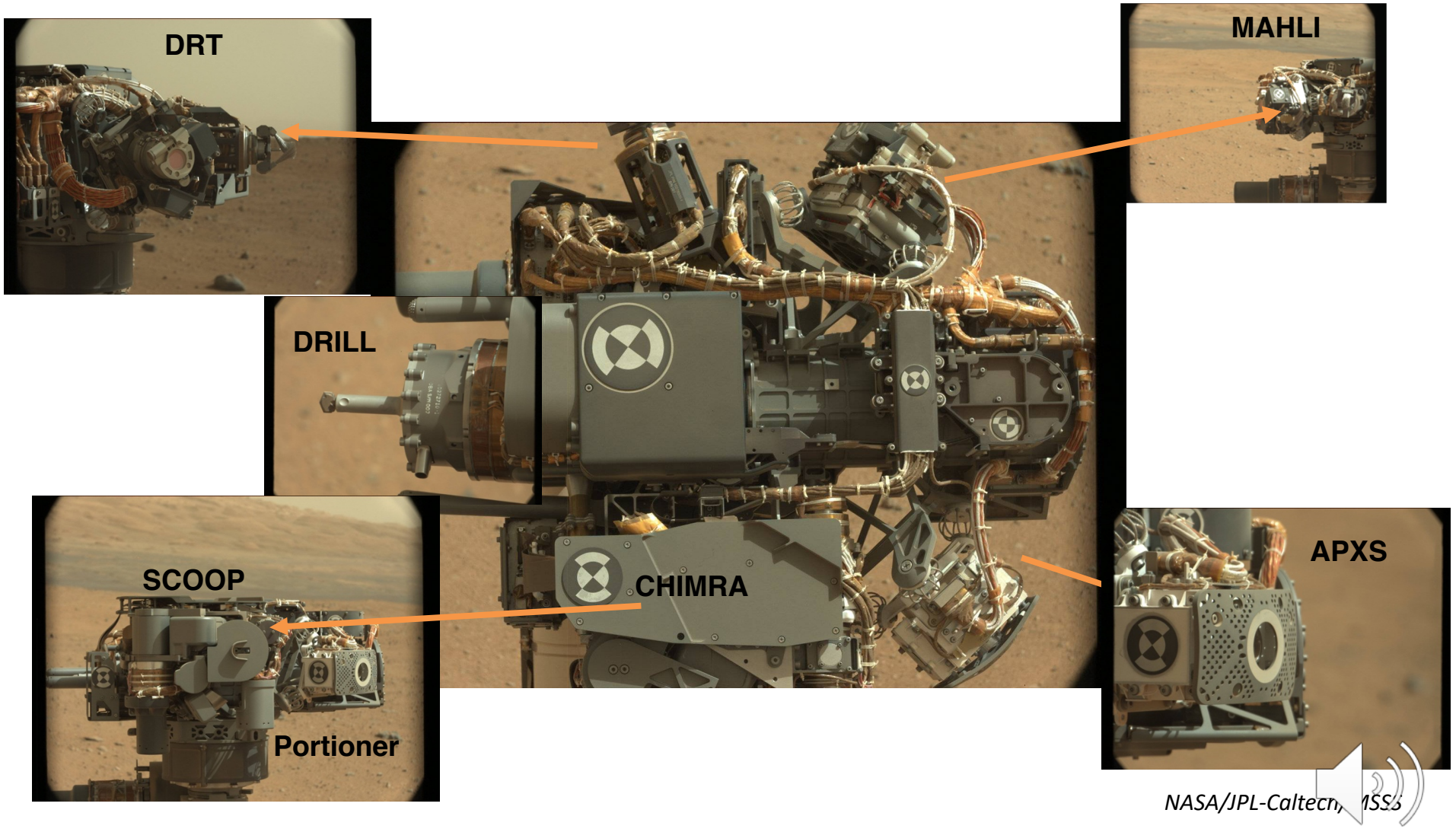
19 mm diameter



MAHLI at 5mm poker standoff

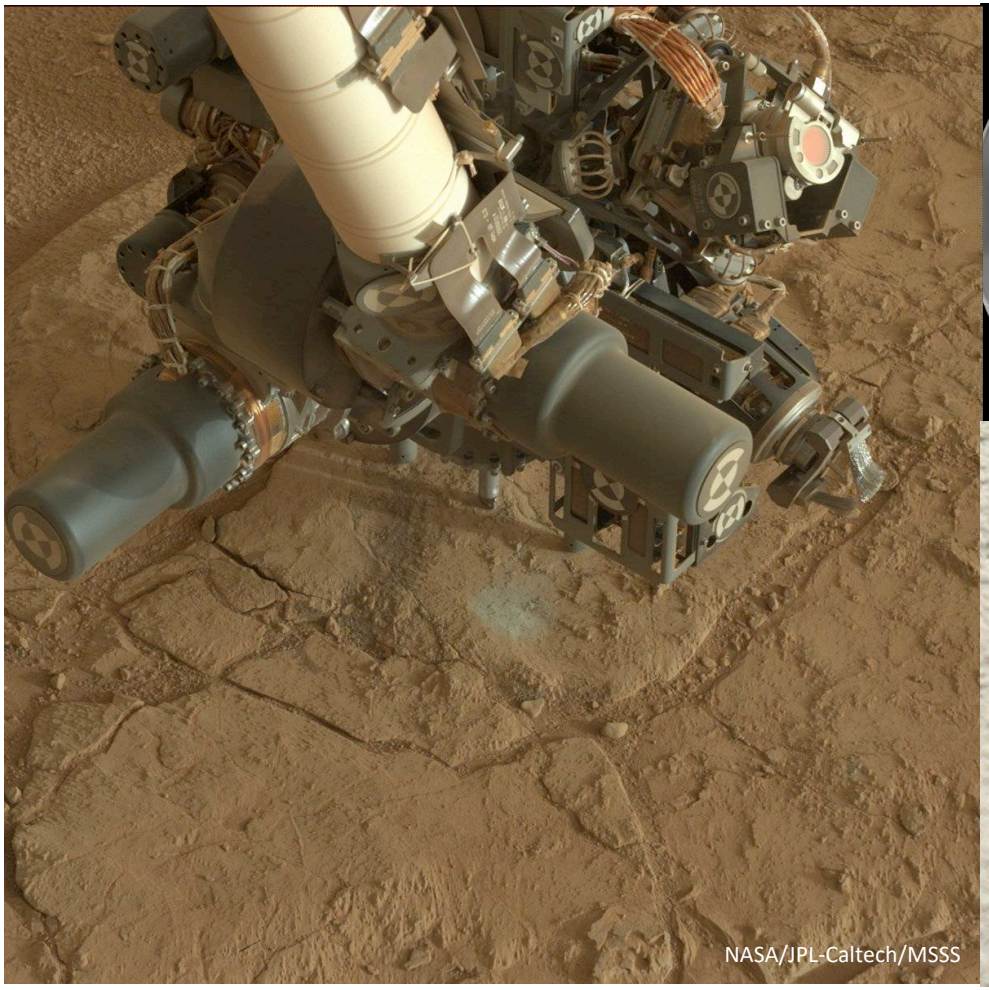
NASA/JPL-Caltech, MSSS

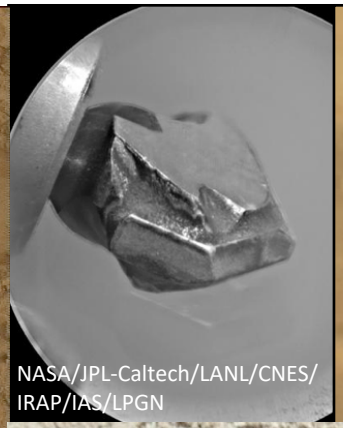
TURRET



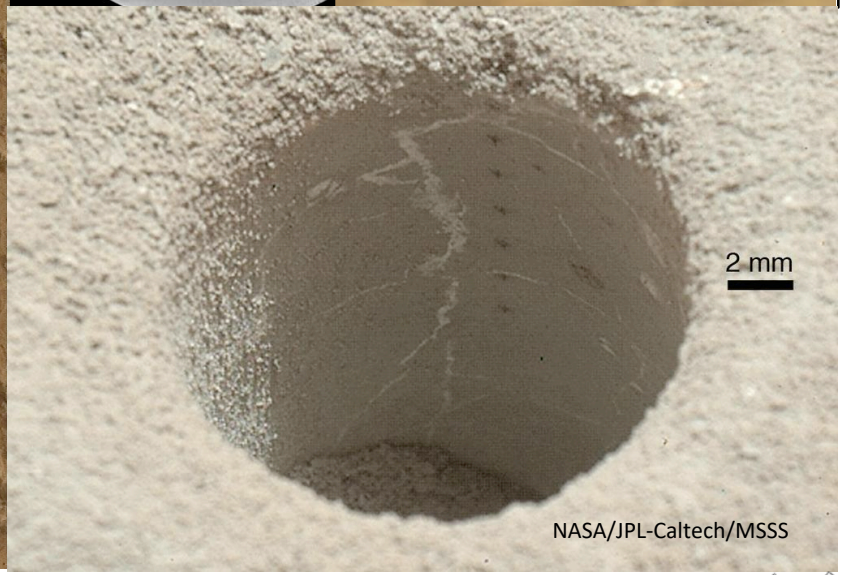
NASA/JPL-Caltech/MSSS

DRILLING

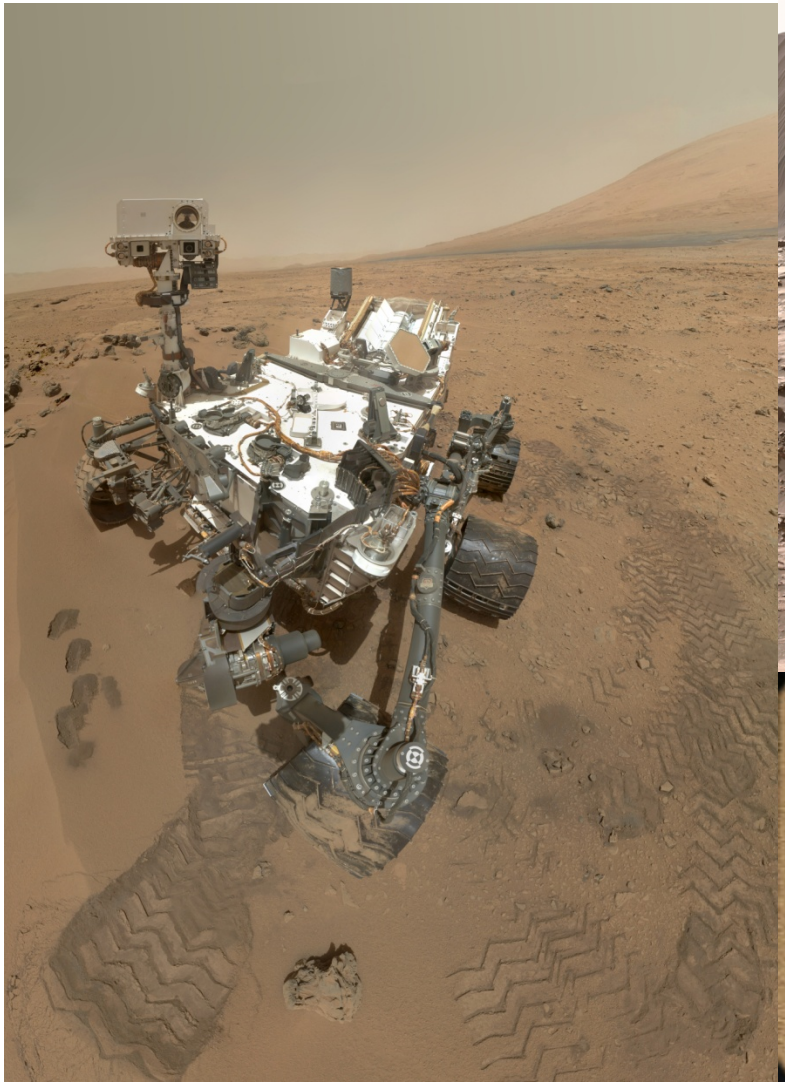

NASA/JPL-Caltech/MSSS

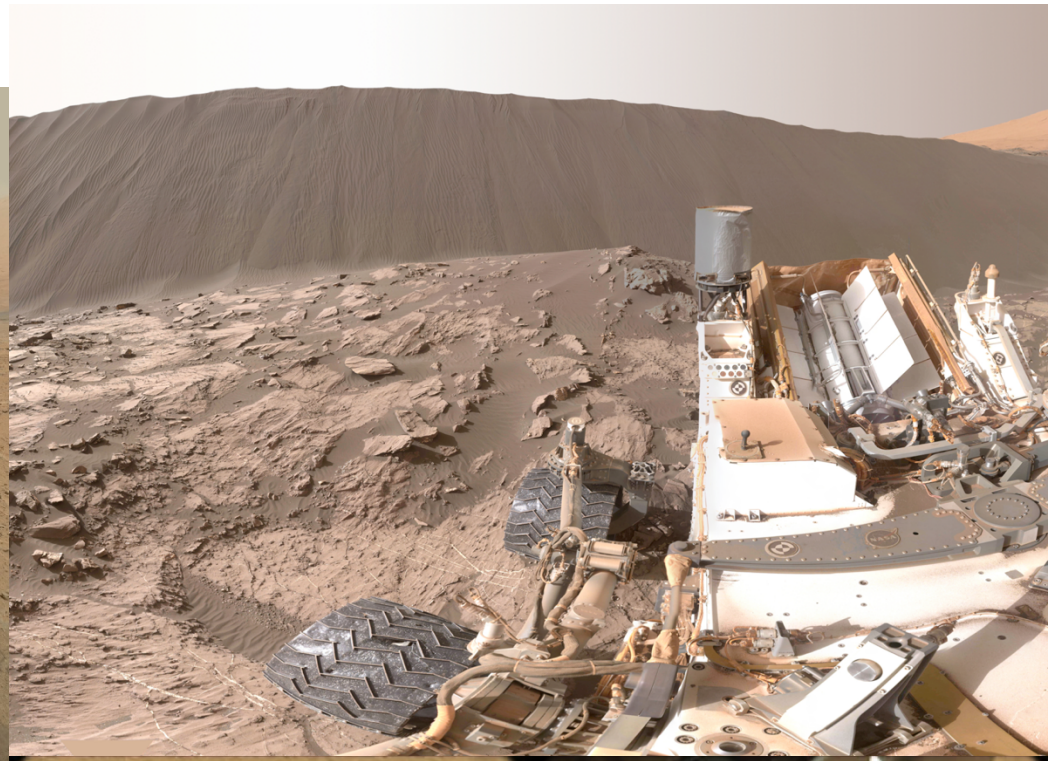

NASA/JPL-Caltech/LANL/CNES/
IRAP/IAS/LPGN

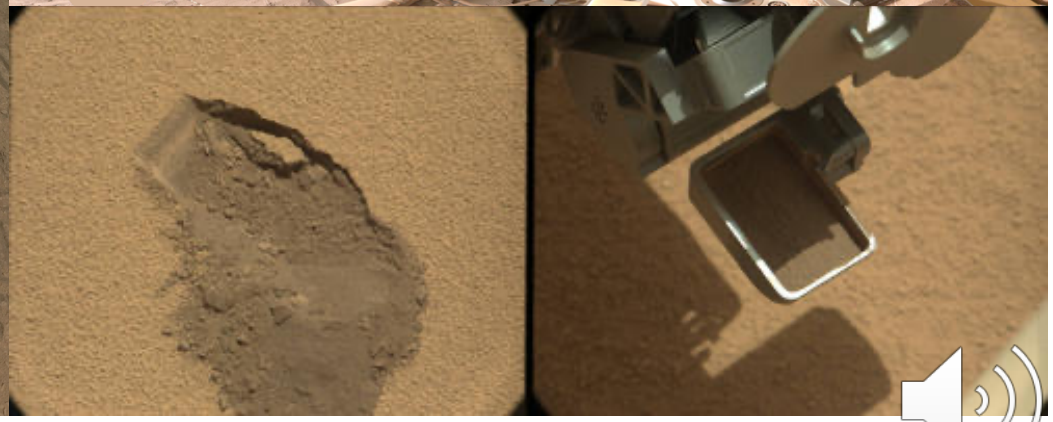

NASA/JPL-Caltech/MSSS


2 mm
NASA/JPL-Caltech/MSSS

SCOOPING

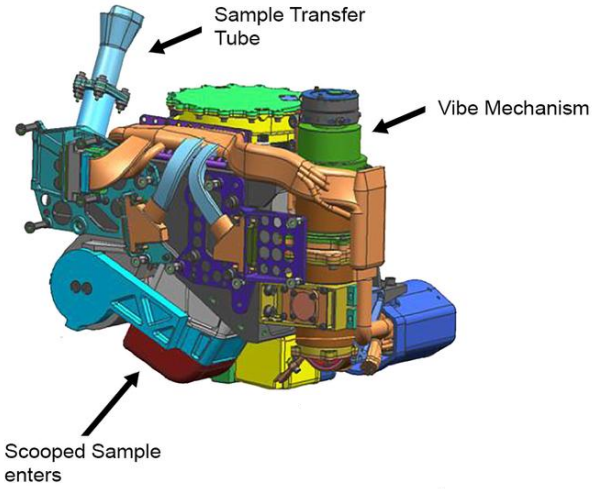




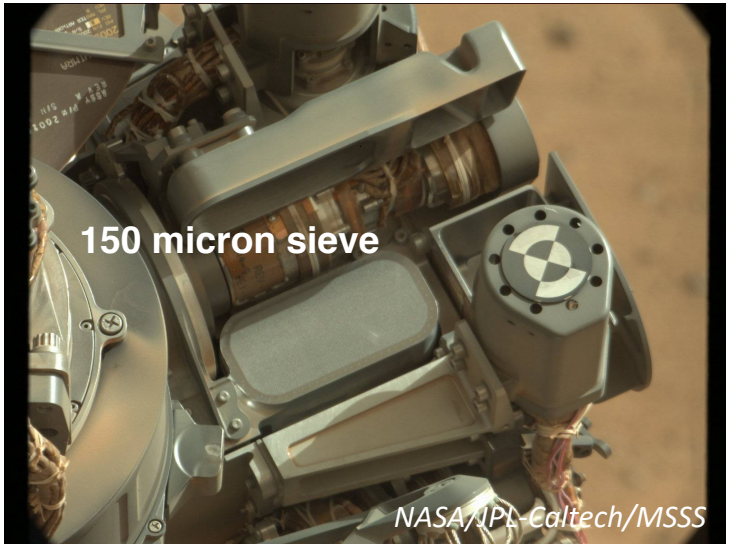


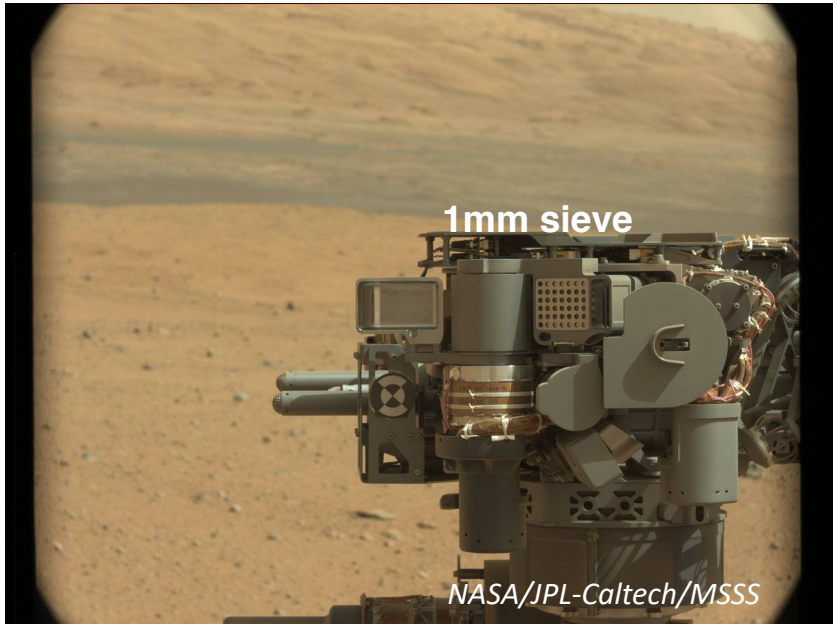
NASA/JPL-Caltech, MSSS

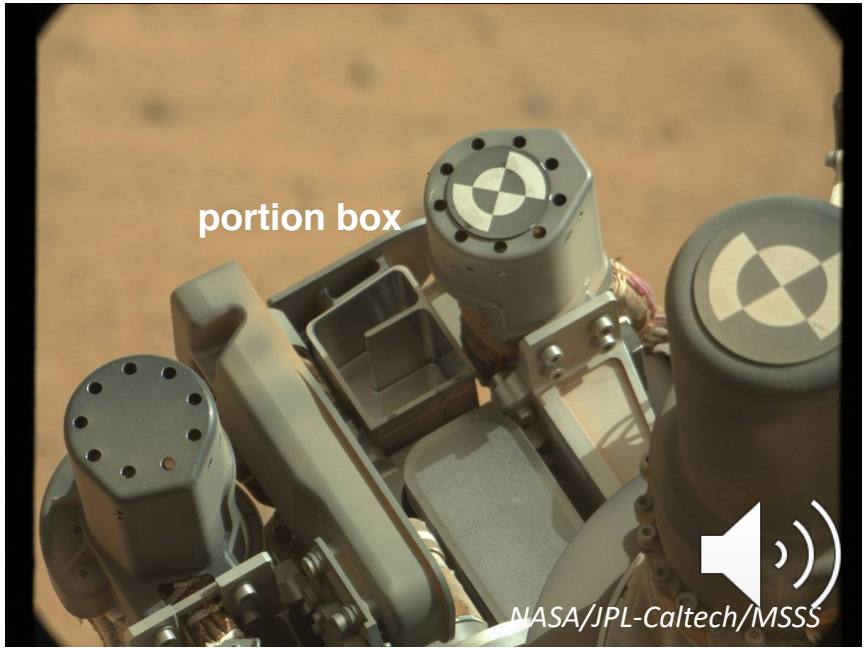
SAMPLE PROCESSING



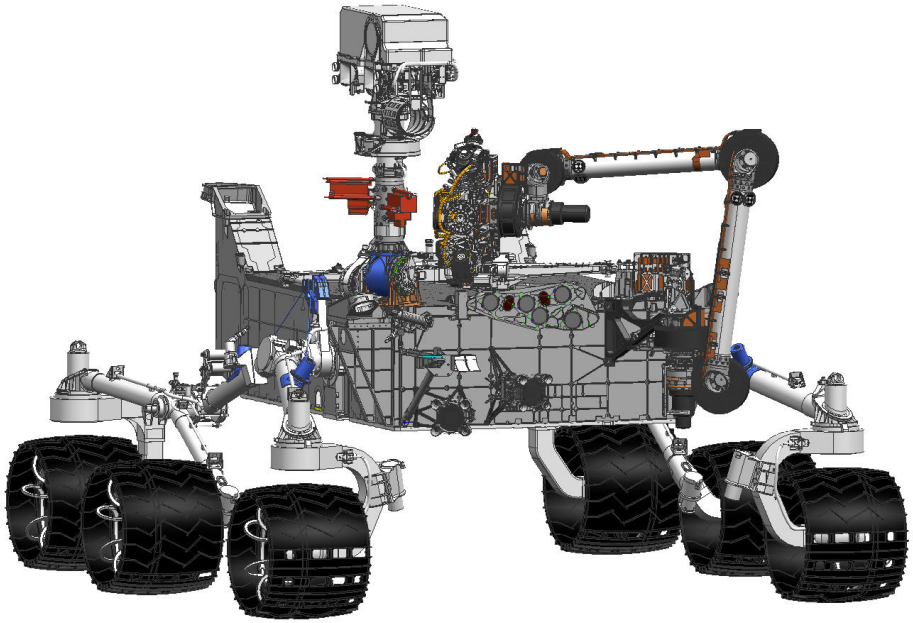
NASA/JPL-Caltech



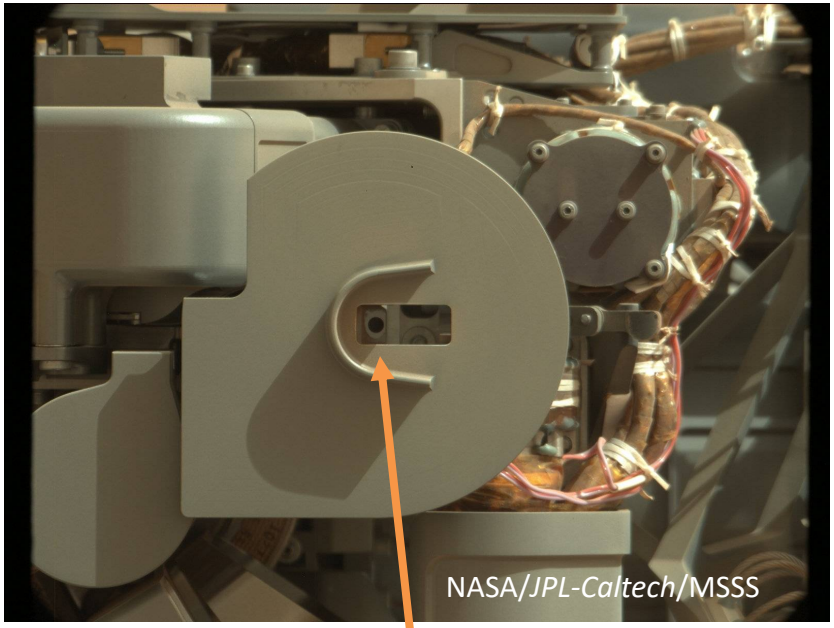




SAMPLE DELIVERY

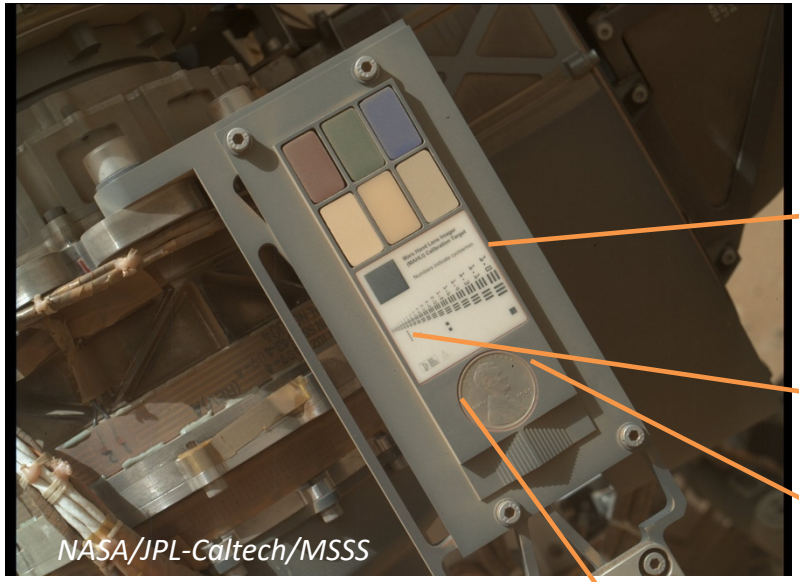


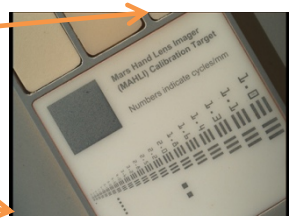
NASA/JPL-Caltech

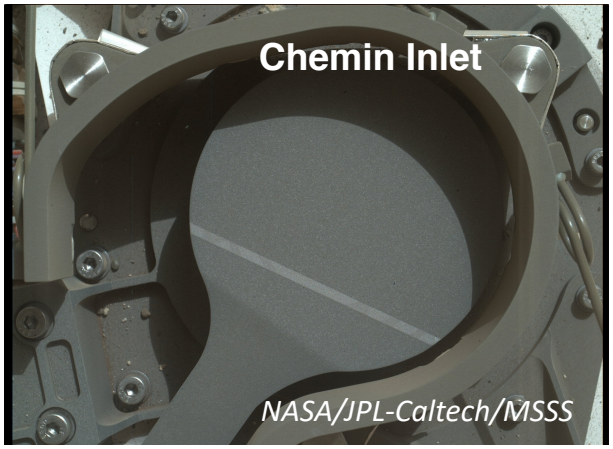


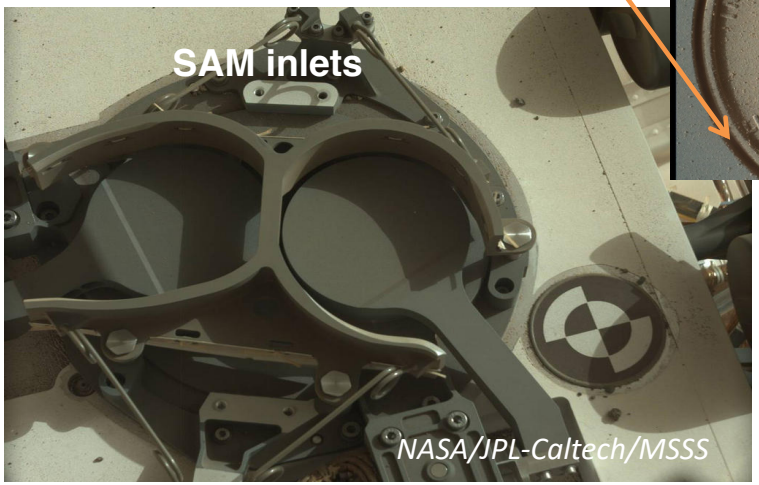
Portion Hole
3 mm diameter

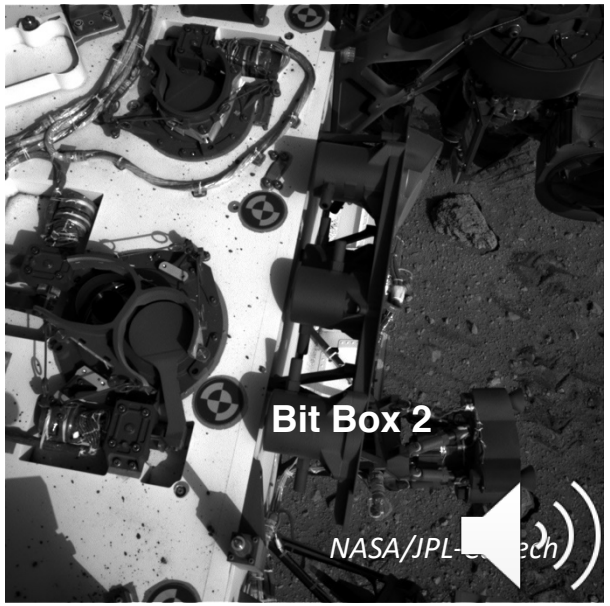
ROVER WORKSPACE











BECAUSE OF THE DISTANCE BETWEEN EARTH AND MARS, WE CAN'T COMMAND THE ROVER IN REAL TIME

MRO, Mars Odyssey, MEX

Deep Space Network
70m (230 foot) antenna

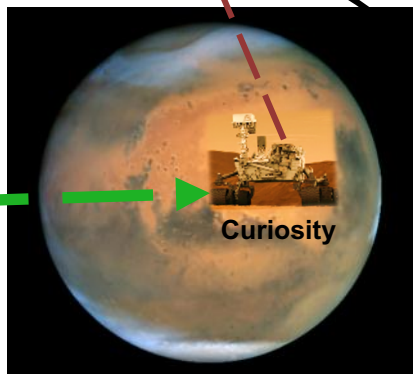
Spain

USA

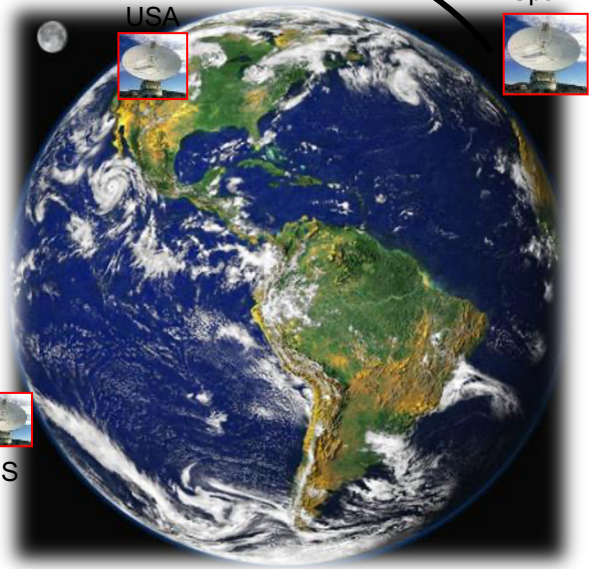
AUS

Up to 24 minute delay

Up to 249,000,000 mi



Mars' Rotation: 24.65 hour Sol



Earth's Rotation: 24 hour day

SSIM – HIGH SPEED FLIGHT SOFTWARE SIMULATION

- Uses actual Flight Software code
  - Can simulate subtle Flight Software state interactions and emergent behavior.
- Makes execution fast, portable, and repeatable by abstracting all hardware interfaces
  - Allows running entirely on Linux whereas the flight system runs VxWorks
- Abstracts flight software modules where modeling a subset of flight software behavior is sufficient.
  - Can simulate thousands of times faster than real time
- Replicates on-board state by using telemetry received on ground to initialize simulation
  - Context sensitive simulation

SSIM – DESIGNED FOR ACCURACY, SPEED AND DETERMINISM

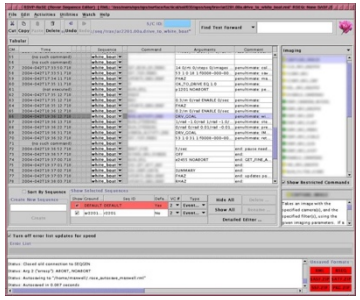
- As in flight software
  - Modules communicate via messages
  - Each task executes an event loop which processes the arriving messages
  - The task waits only on message arrival, at only one point in the code, and acts on the message according to the modules top-level state machine
- Designed for repeatable determinism
  - Flight software is multi-threaded concurrent
  - SSim is Single-threaded concurrent
  - Flight software initializes and activates modules and spawns tasks
  - SSim initializes and activates modules without spawning tasks

SSIM HIGH LEVEL INPUT/OUTPUT

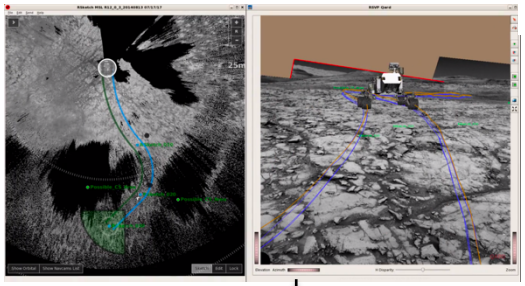
TELEMETRY FROM ROVER

SSIM DERIVED INITIAL STATE

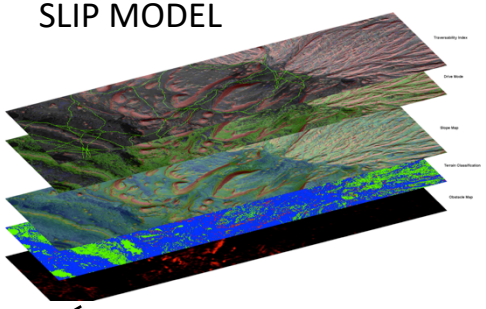
COMMANDS



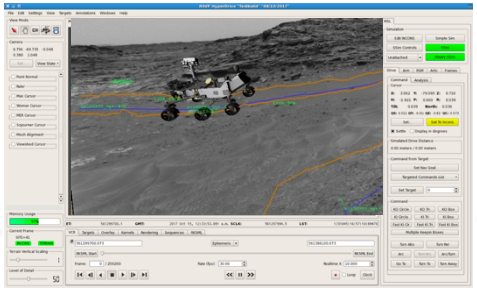
SKETCH



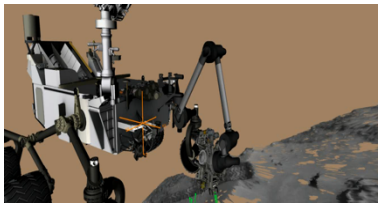
TERRAIN MODEL SLIP MODEL



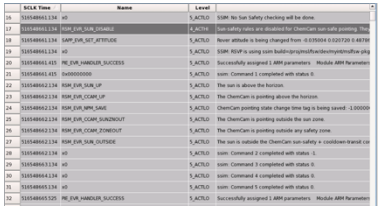
EMBEDDED SSIM



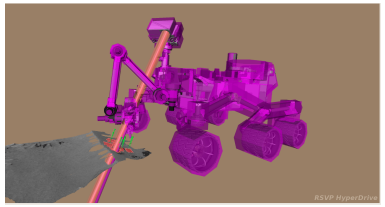
FWD/INVERSE KINEMATICS



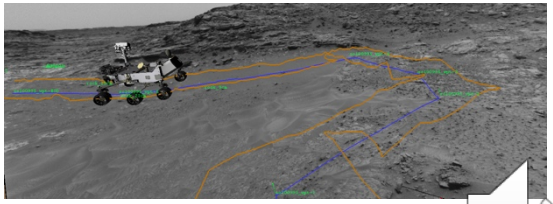
TELEMETRY



COLLISION MODEL

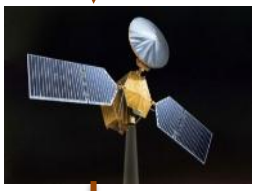


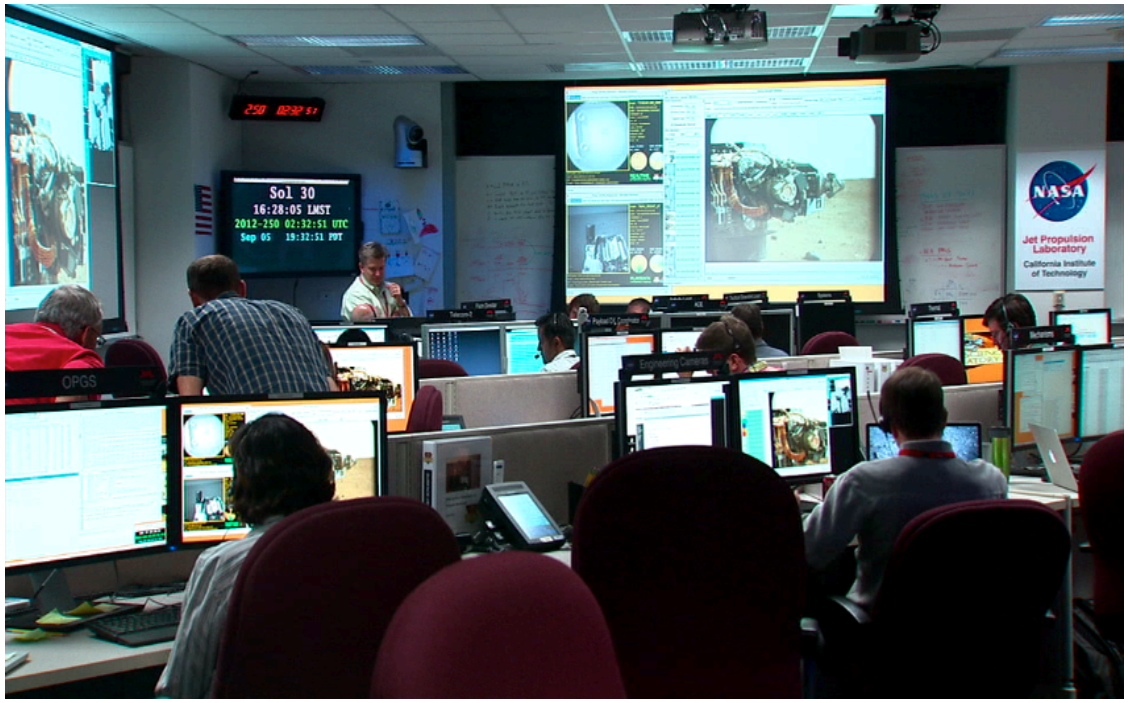
STATE HISTORY



ROVER OPERATIONS

Rover Awake | Rover Asleep | Rover Awake





Data

Downlink analysis

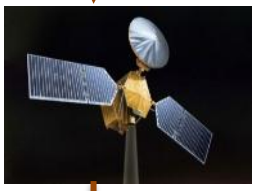
Commands for 1-3 Sols

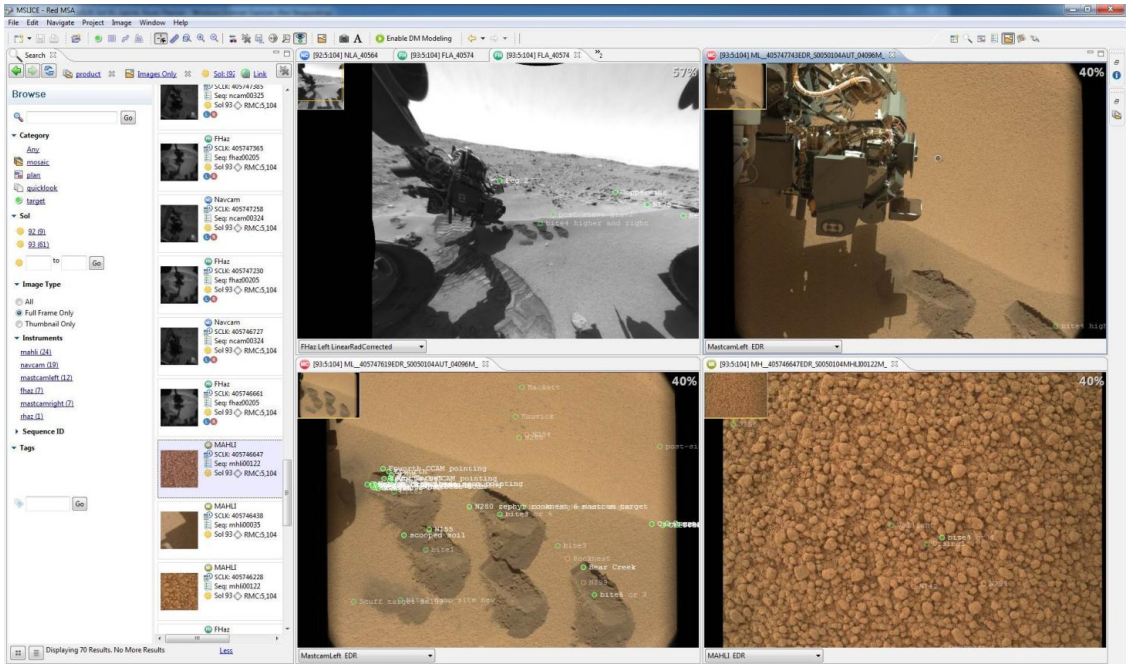
ROVER OPERATIONS

Rover Awake

Rover Asleep

Rover Awake





Data

Planning

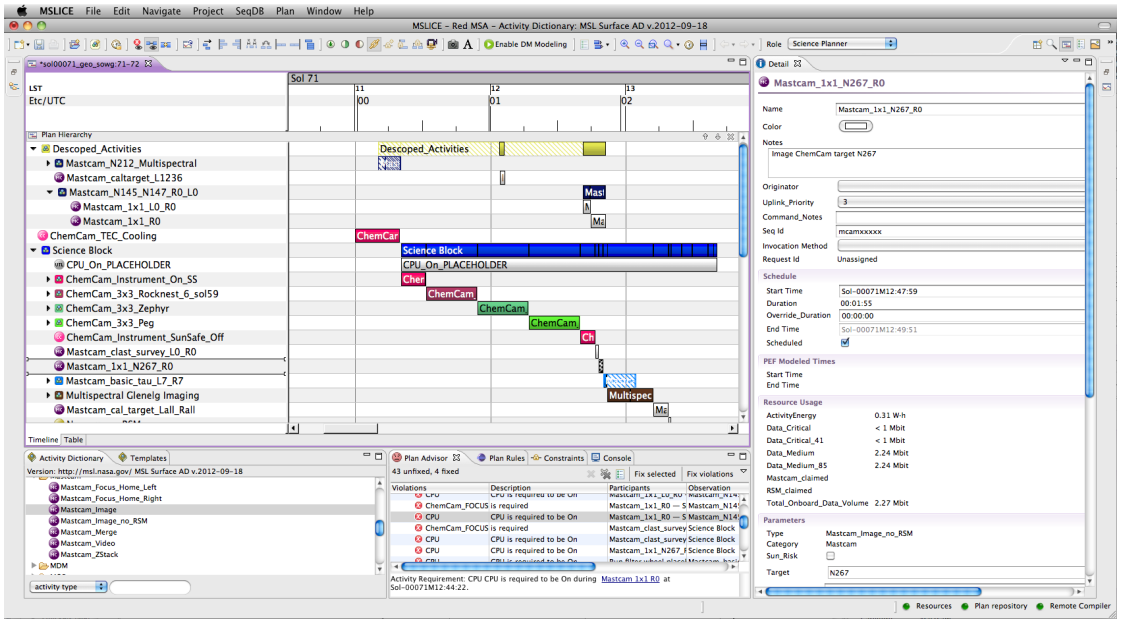
Commands for 1-3 Sols

ROVER OPERATIONS

Rover Awake

Rover Asleep

Rover Awake



Data

Planning

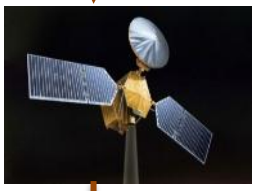
Commands for 1-3 Sols

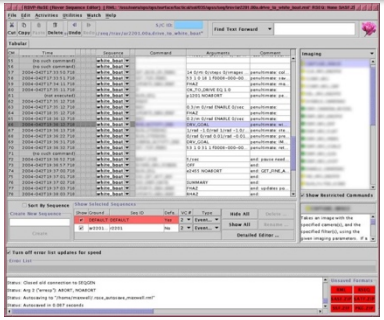
ROVER OPERATIONS

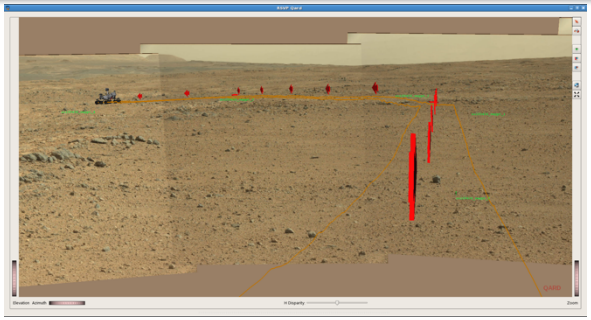
Rover Awake

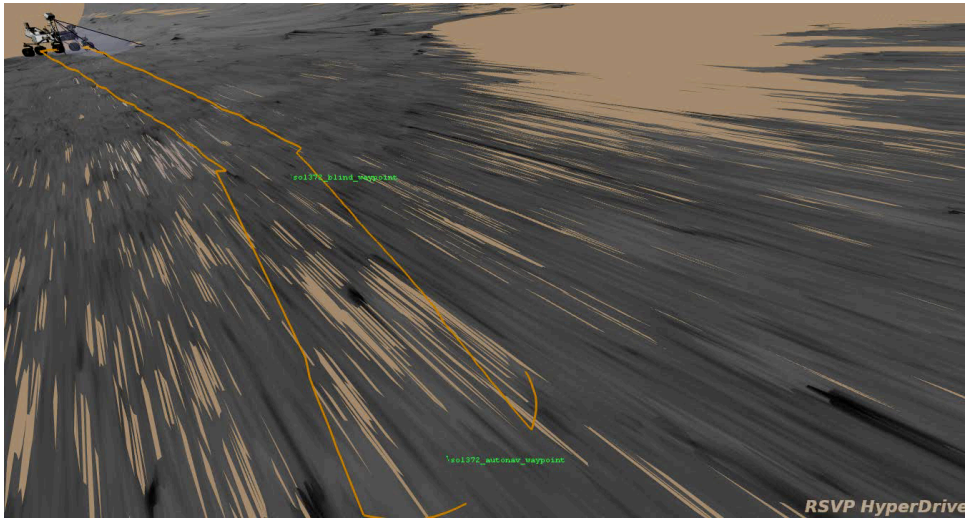
Rover Asleep

Rover Awake









Data

Sequencing

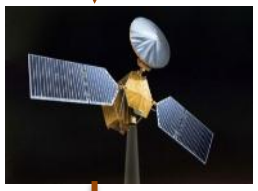
Commands for 1-3 Sols

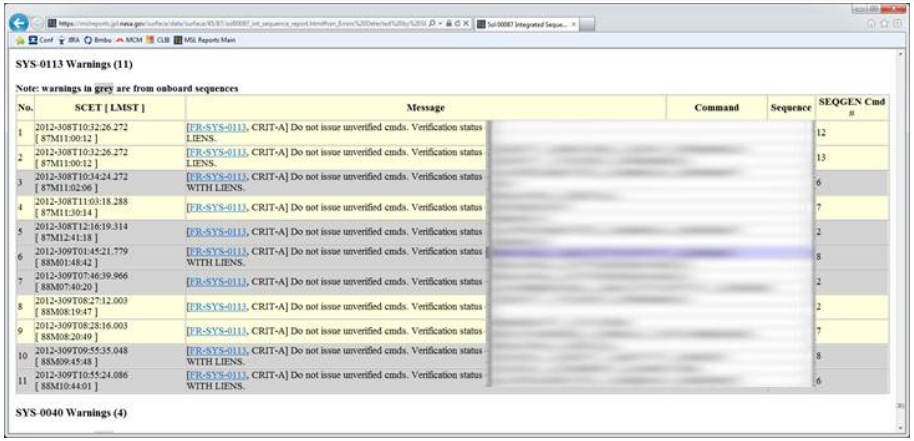
ROVER OPERATIONS

Rover Awake

Rover Asleep

Rover Awake



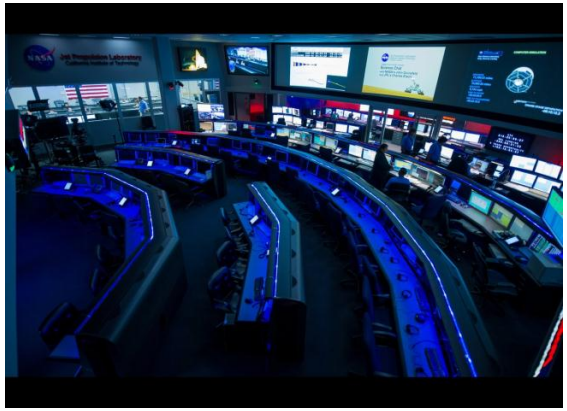


SYS-0113 Warnings (11)

Note: warnings in grey are from onboard sequences

No.	SCET [LMST]	Message	Command	Sequence	SEQGEN Cmd #
1	2012-308T10:32:26.272 [87M11:00:12]	[FR-SYS-0113, CRIT-A] Do not issue unverified cmds. Verification status LIENS.			12
2	2012-308T10:32:26.272 [87M11:00:12]	[FR-SYS-0113, CRIT-A] Do not issue unverified cmds. Verification status LIENS.			13
3	2012-308T10:34:24.272 [87M11:02:06]	[FR-SYS-0113, CRIT-A] Do not issue unverified cmds. Verification status WITH LIENS.			6
4	2012-308T11:03:18.288 [87M11:30:14]	[FR-SYS-0113, CRIT-A] Do not issue unverified cmds. Verification status			7
5	2012-308T12:16:19.314 [87M12:41:18]	[FR-SYS-0113, CRIT-A] Do not issue unverified cmds. Verification status			2
6	2012-309T01:45:21.779 [88M01:48:42]	[FR-SYS-0113, CRIT-A] Do not issue unverified cmds. Verification status WITH LIENS.			8
7	2012-309T07:46:39.966 [88M07:40:20]	[FR-SYS-0113, CRIT-A] Do not issue unverified cmds. Verification status			2
8	2012-309T08:27:12.003 [88M08:19:47]	[FR-SYS-0113, CRIT-A] Do not issue unverified cmds. Verification status			2
9	2012-309T08:28:16.003 [88M08:20:49]	[FR-SYS-0113, CRIT-A] Do not issue unverified cmds. Verification status			7
10	2012-309T09:55:35.048 [88M09:45:48]	[FR-SYS-0113, CRIT-A] Do not issue unverified cmds. Verification status WITH LIENS.			8
11	2012-309T10:55:24.086 [88M10:44:01]	[FR-SYS-0113, CRIT-A] Do not issue unverified cmds. Verification status WITH LIENS.			6

SYS-0040 Warnings (4)

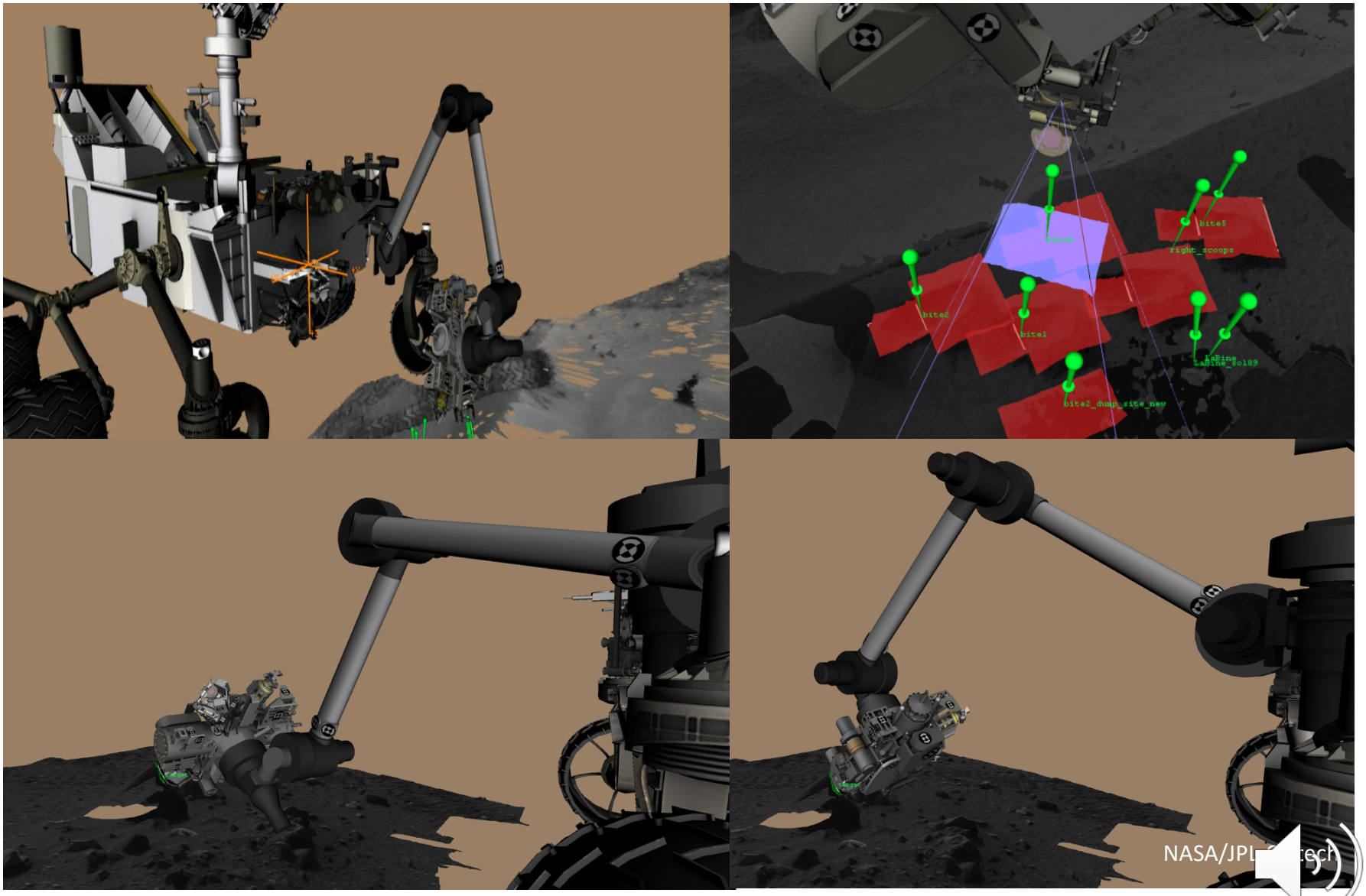


Data

Validation and Uplink

Commands for 1-3 Sols

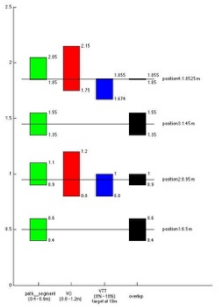
SEQUENCING AND VALIDATING ROBOTIC OPERATIONS

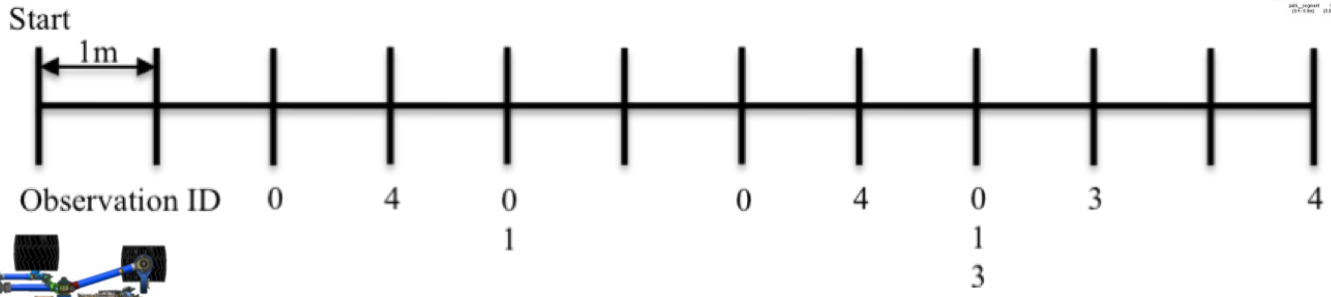


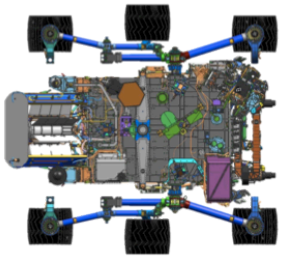
NASA/JPL-Caltech

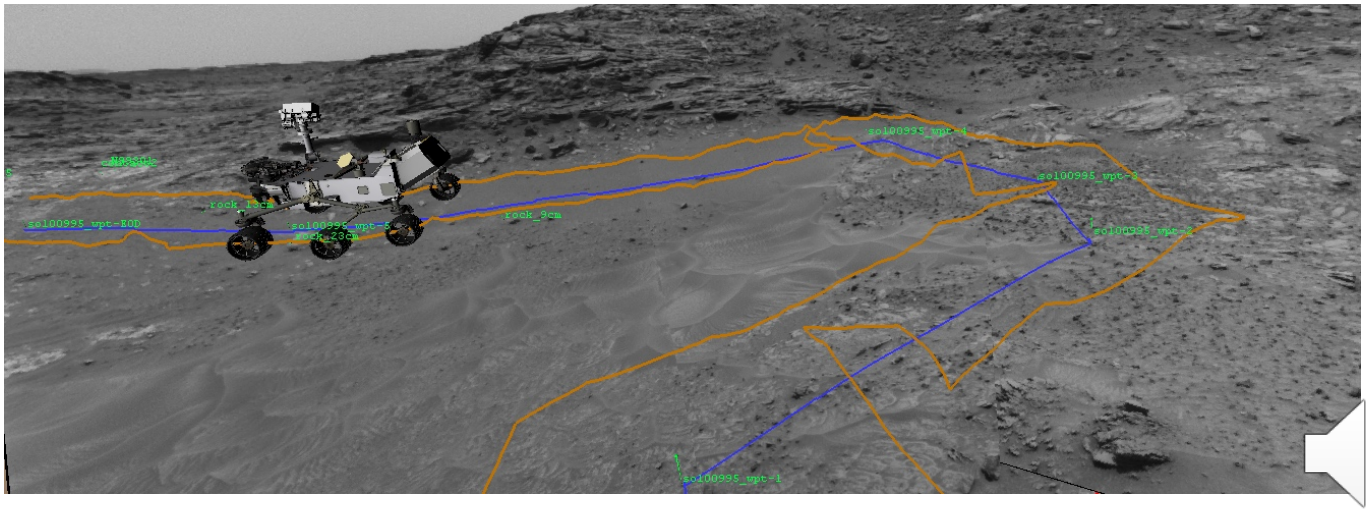
PREDICT PLAN EXECUTION

- Example:
  - Observation 0: mcam00010, every 2 steps, maximum 4 calls
  - Observation 1: dan_01234, every 3.5 meters, maximum 100 calls
  - Observation 3: ncam00000, after sclk 307512588, maximum 2 calls
  - Observation 4: ncam00030, every 10 minutes, maximum 4 calls

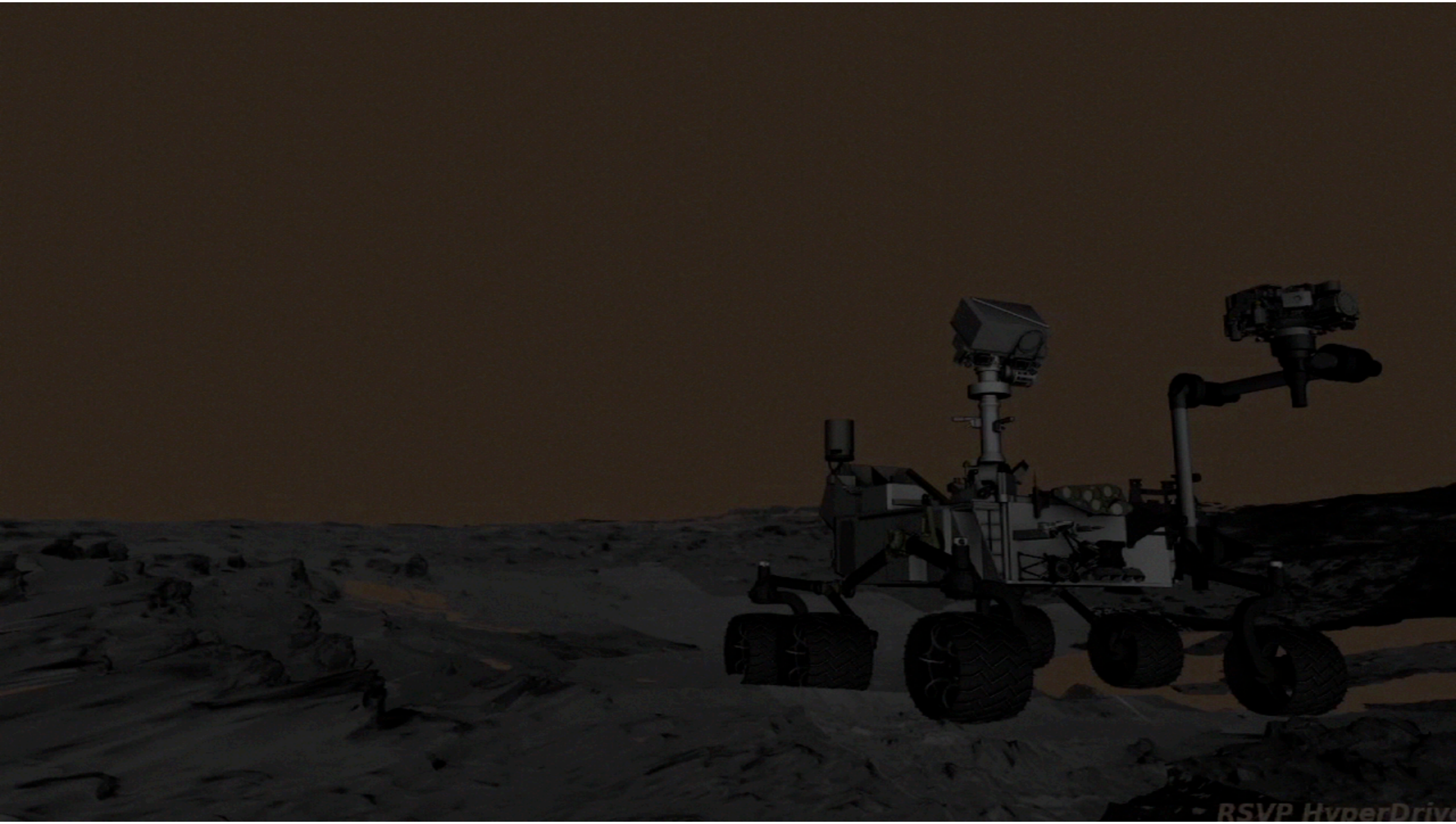




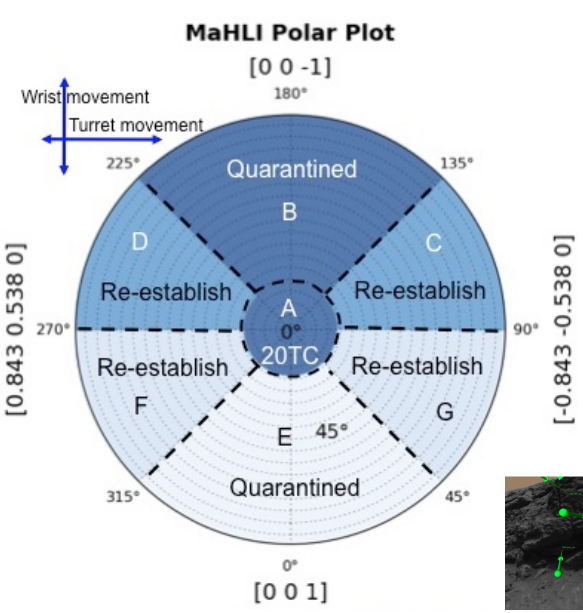


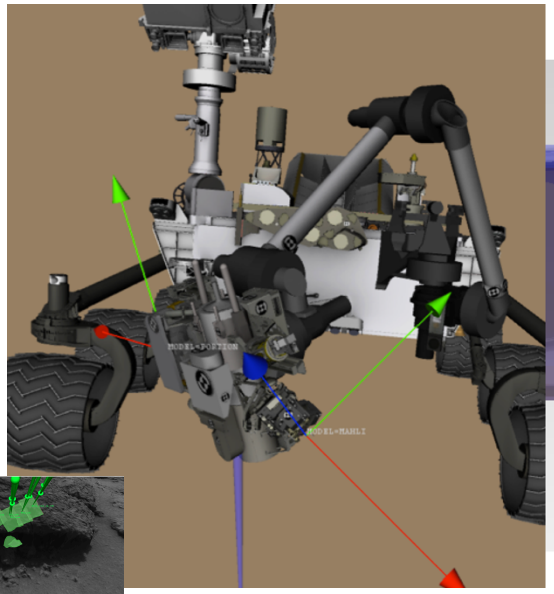


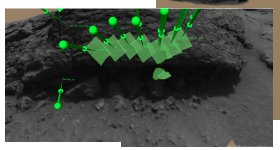
FIRST TOUCH AND GO

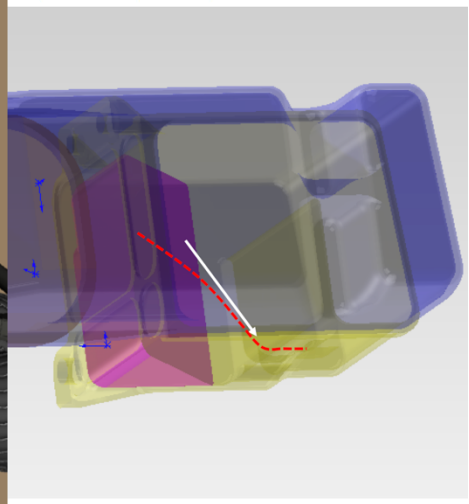


EXTENDING FLIGHT CAPABILITY AND MODELING UNCERTAINTY

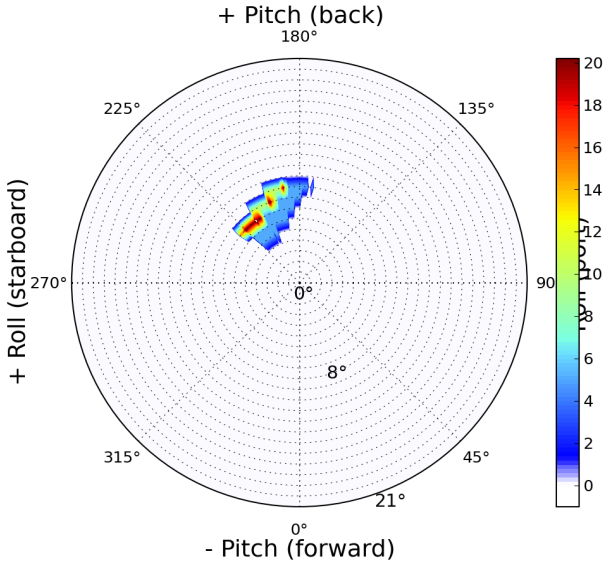




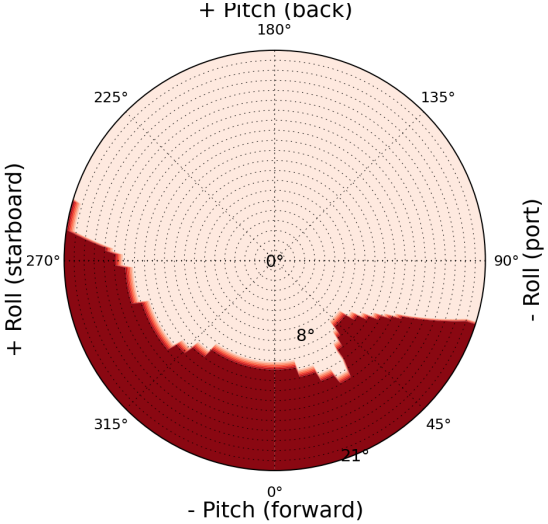




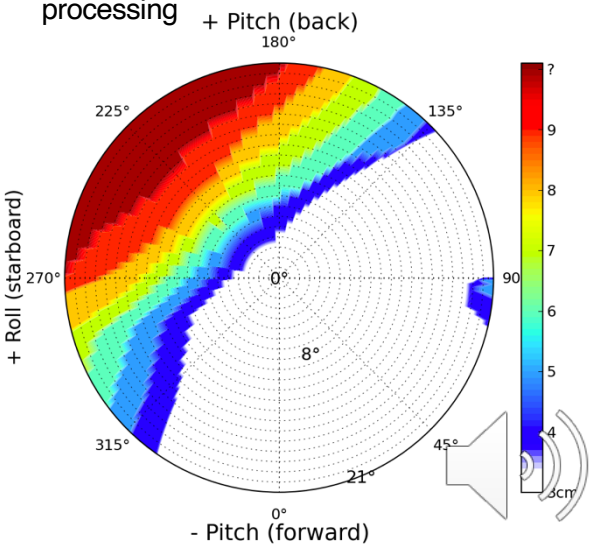
SAM safing script in but no out constraint



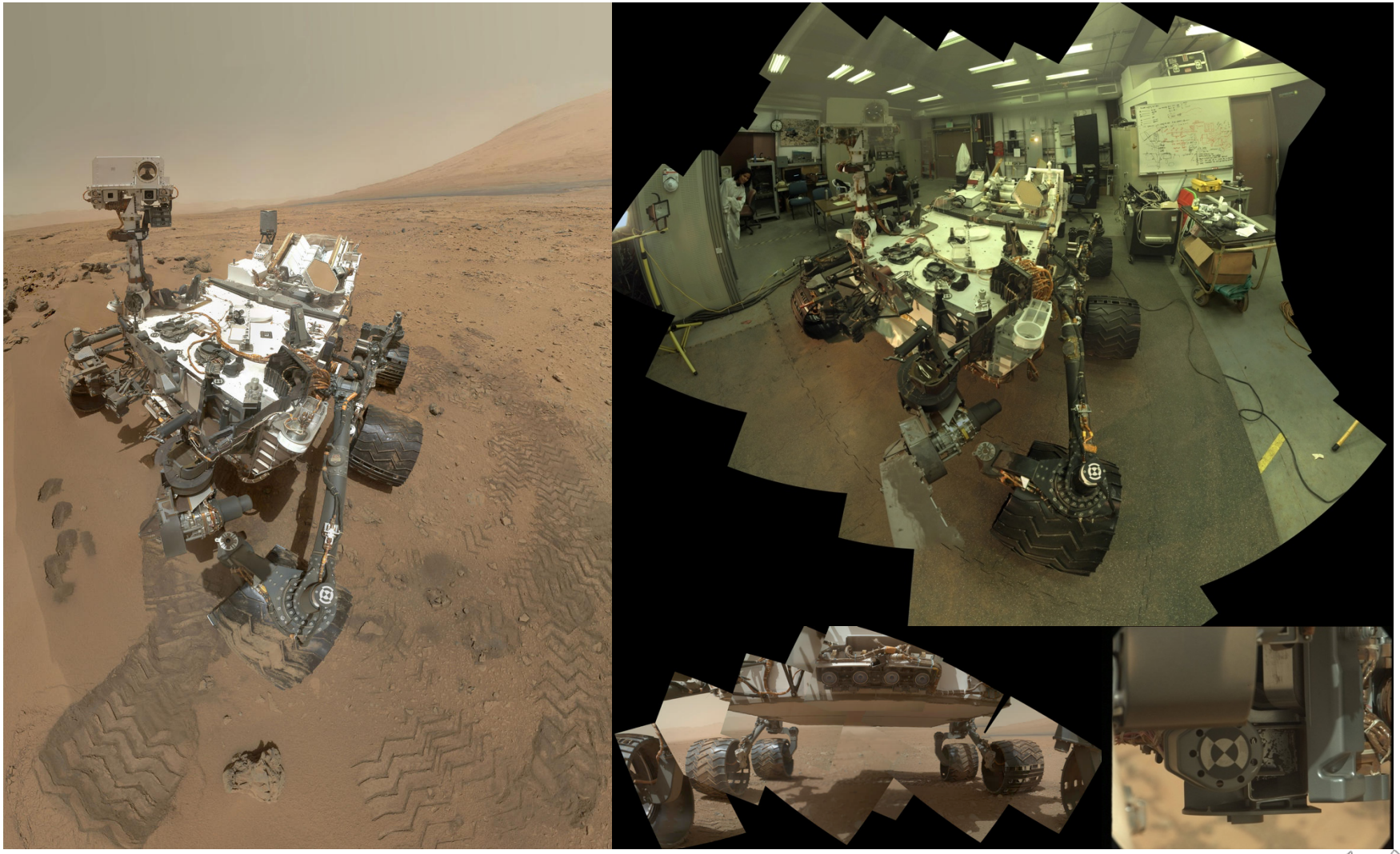
Dropoff to observation tray with portioner



Dropoff to SAM1 via 150um sample processing

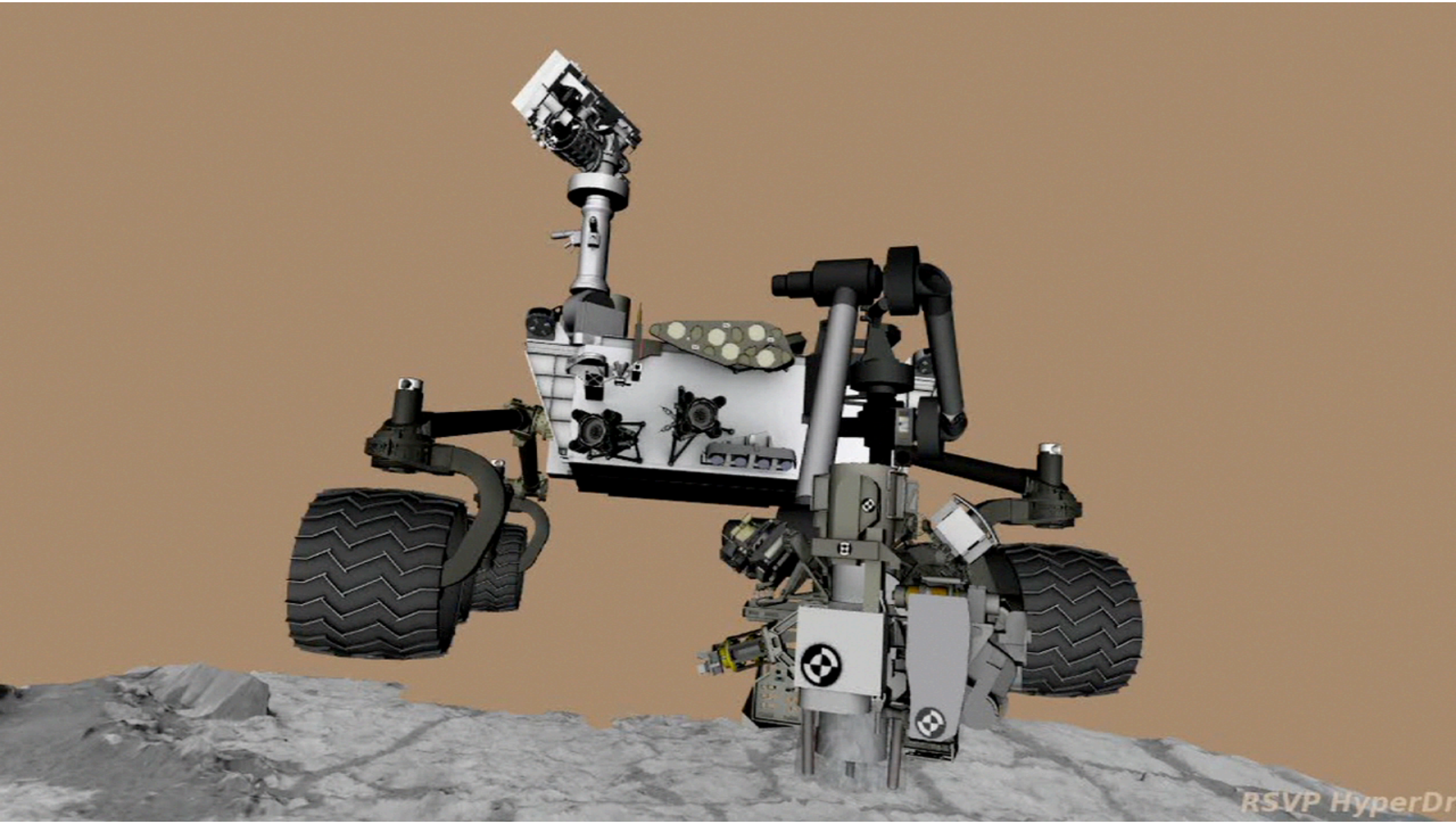


ROVER SELF INSPECTION



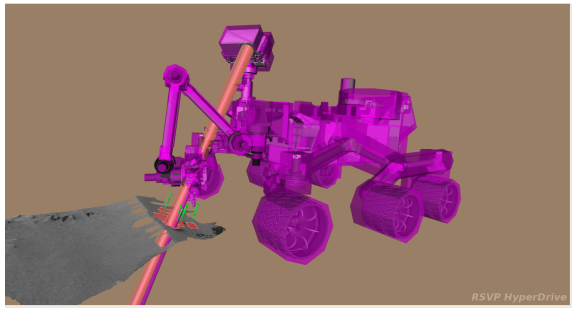
NASA/JPL-Caltech/M[illegible]S

SAMPLING

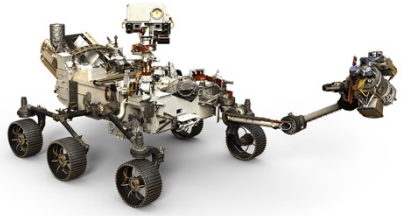


SSIM IMPACT

- Critical for MSL Development and Operations
  - Used for every single sol on MSL surface operations with robotics activities
  - Other teams have come to depend on it (Chemcam, Mastcam, MAHLI)
  - Avoids cases where rover execution significantly different from simulation
  - Strategic development of activities, such as sampling
  - Robotic arm moves for ATLO and Testbed



- M2020 adopted SSIM for all surface FSW simulation
  - On MSL only simulated robotics FSW
  - M2020 plan is to simulate all surface flight software
    - Mastcam-Z, MEDA, MOXIE, PIXL, SHERLOC, RIMFAX, SuperCam, SHERLOC, engineering sub-systems (thermal, power, communications, fault protection, data management…).
  - Skip human review of commands
  - Commanding spacecraft at higher and higher level



- Concept extended beyond operations use cases

SUMMARY

- High speed simulations such as SSim that use the actual Flight Software can provide a powerful analysis, testing and operations capability. They remove the need to replicate in models the behavior of increasingly complex Flight Software.
- The determinism of the simulation makes it valuable for integrated software regression testing.
- Future missions and robotic systems can benefit from following this approach. Regardless of the level of autonomy, there is eventually human intent behind robotic systems. SSim provides a capability for human operators to quickly check if their intent is correctly captured by the robot prior to execution.
- It's speed makes it an effective regression testing tool for simulating with a variety of different initial and intermediate states and environmental feedback.

AUTHORS BIOGRAPHY

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- Vandi Verma is a Robotics Technologist and Supervisor of the Operable Robotics group in the Mobility and Robotic Systems Section at NASA JPL.
- She designed and developed MSL's Software Simulator ("SSIM"); has been a rover planner on MER and MSL since 2008; helped develop MSL's sample processing and AEGIS autonomous flight software; and is working on Robotic Arm and Sample Caching algorithms for Mars 2020.

She has a Ph.D. in Robotics from Carnegie Mellon University. Her thesis was on particle filters for robot fault detection and identification.

- Contact: leger@google.com
- Chris Leger was the Surface FSW Development Lead for the Mars Science Laboratory Mission, and a developer for the robotic arm and motor control interface flight software, and SSim.
- He previously worked as a rover driver and flight software developer for the Mars Exploration Rover (MER) mission, and as a mobility and motor control flight system engineer for the Mars Science Laboratory mission.

Dr. Leger received a BS in Computer Engineering and MS and PhD degrees in Robotics from Carnegie Mellon University. He currently works at Google, Mountain View, CA.